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Extreme Design Loads Calibration of Offshore Wind Turbine Blades through Real Time Measurements

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Abstract

Blade Root flap and Edge moments are measured on the blades of a 3.6MW offshore wind turbine in normal operation. Ten minute maxima of the measurements are sampled to determine the extreme blade root flap moment, edge moment and resultant moment over six month duration. A random subset of the measurements over a week is taken as input to stochastic load extrapolation whereby the one year extrapolated design extreme is obtained, which are then compared with the maximum extremes obtained from direct measurements over a six month period to validate the magnification in the load levels for the blade root flap moment, edge moment obtained by extrapolation. The validation yields valuable information on prescribing the slope of the local extrapolation curve at each mean wind speed. As an alternative to determining the contemporaneous loads for each primary extrapolated load, the blade root resultant moment is extrapolated. This is found to possess smaller scaling factors in measurements over six months as compared to both the flap and edge moments, indicating that the contemporaneous load component of an extrapolated load should possess much smaller magnitude than its maxima.

1. Introduction

The IEC 61400- 3 [1] requires that the extreme loads over the rotor of an offshore wind turbine in

normal operation as determined using limited computer simulations be extrapolated to a 50 year return period. Extrapolated extreme load magnitudes can possess large uncertainties based on the probability distribution chosen, the number of data points used to fit probabilistic distribution functions and the interaction of the control system with the wind turbulence and several studies to enable robust prediction of the extrapolated extreme load level have been made [2]. This load case (DLC1.1) is often design driving for the blade tip deflection and the blade ultimate strains. Therefore robust methods that determine the design extreme load level are crucial. A key objective of this study is to determine a validated method for load extrapolation and contemporaneous load magnitudes which bound the magnification of the extrapolated load value as compared to the maximum in the sampled load set. The component design extreme loads are not a solitary quantity since the coincident secondary loads at the instant of the extreme primary load are required in component design. Usually the blade edge moment is determined as the coincident load for the extreme flap moment at the instant of the extreme flap moment in simulations. However upon extrapolation of a load level, the information on the coincident loads at the extrapolated load level is lost. The IEC 61400-1 standard [3] provides informative methods to select the contemporaneous loads based on the mean value of coincident load

over sampled extremes in the simulations or by scaling the coincident loads from simulations with a scale factor equal to the ratio of the extrapolated load value to the largest simulated load value. However such methods are not proven and may render the design extreme load level to be ambiguous. Here in this investigation the magnification in the flap and edge moments as obtained through the measurements over a six month period is compared with the magnification in the corresponding resultant moment to analyze the expected magnitude of the contemporaneous moments to be taken with a primary extrapolated moment.

2. Measurement System

A Siemens 3.6MW, 107m rotor diameter offshore wind turbine on an operational wind farm has been completely instrumented to measure loads over all its components [4]. The turbine blades are equipped

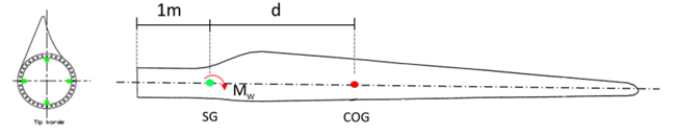


Figure 1: Strain gauge mounting on the blade and moment measured on the gauge due to blade weight.

averaged rotational speed, anemometer wind speed, power production, blade pitch angle and turbine yaw direction.

The main wind direction at the site is WWS, but the turbine under analysis is in wake in the main wind direction and facing free winds in SSE. The partial wind climate in SSE (frequency 10.4%) corresponds to an annual wind speed average of 9.97 m/s and a Weibull exponent k-parameter of 2.65. As a large part of the wind turbine operation is in the wake, this sector is also considered in the extreme loads analysis.

Apart from the loads instrumentation, SCADA based data from surrounding wind turbines are

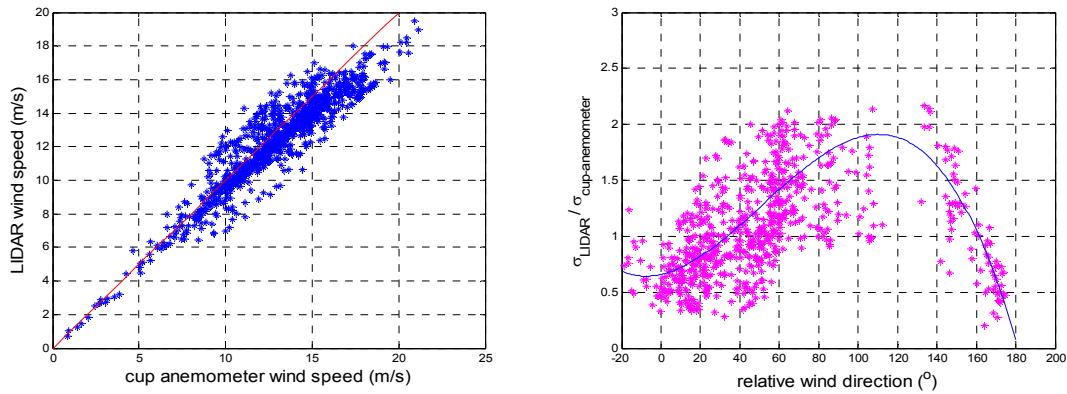


Figure 2 : a) Linear regression between the 10min mean wind speed measured by the nacelle LIDAR and the cup-anemometer. b) Ratio between wind speed standard deviation estimated by nacelle LIDAR and by the nacelle cup-anemometer.

with 4 strain gauges, which are mounted 1m from the blade root, for measurement of the flap and edge moments as shown in Fig. 1. The loads measured on the turbine are logged as high frequency time series, from which additional statistics is processed. A SCADA system on the turbine transmits ten minute

obtained to correlate measurements such as wind direction and wake effects. The blade strain gauges are calibrated through a gravity load based experiment during stand still of the turbine. A LIDAR is also mounted on the turbine nacelle to verify the mean wind speed measurements from the

anemometer [5]. The LIDAR was calibrated under standard conditions measured at the Høvsøre test site in Denmark. A comparison of wind velocity measurements from the LIDAR on the nacelle with the cup anemometer of the turbine when the turbine is not rotating is shown in Fig. 2, which shows that the nacelle anemometer measured mean wind velocity is close to the predictions from the LIDAR. However this specific LIDAR was not sufficiently accurate in measuring turbulence as can be seen in the wide variation of the measured standard deviation against wind direction in Fig.2.

The flap and edge moments on all three blades of the turbine are recorded continuously in a database under all operating and stand still conditions from May 2012. However there was a six month period of standstill of the wind turbine due to an unexpected component failure during which time the measurements are not used. To utilize the measurements for extreme load identification, the measurements under normal operation of the turbine between 5m/s and 25m/s mean wind speeds are used. Further both wake sectors and free stream sectors are used since the extreme design of the turbine should be reliable under both conditions.

3. Load Extrapolation Methodology

The extreme load extrapolation is based on the IEC 61400-1 Ed.3 [3] and the stochastic distribution applied to the tail of the extreme loads data is a Gumbel distribution with a distorted quadratic exponent as described in [6]. The Gumbel distribution with a quadratic exponent is the theoretical solution for asymptotic extreme values and is proven to converge to the 50 year exceedance probabilities for Poisson processes [7].

The quadratic Gumbel distribution is a tail distribution and is valid only in the region that is beyond 1 Std. Deviation (σ) from the mean. We are seeking to represent the last 2% quantile of extreme

loads through this distribution for load extrapolation and herein it has been shown to produce an optimal fit to the sampled loads [6]. The long term probability of exceedance P that the extreme load F_e exceeds a given level F is thereby given by Eq. (1) wherein the probability of the mean wind speed has been assumed to be Rayleigh distributed. In Eq. (1), a, b, c are the coefficients of the parametric fit to the extreme loads data at a mean velocity of v_i and n_i is the number of uncorrelated extreme loads at each mean wind speed. The target 50 year probability of exceedance is $3.8\text{e-}07$ and the one year probability level is $1.9\text{e-}05$.

Utilizing this methodology, a random sample of blade root flap maximum moments as measured on one of the blades of the 3.6MW wind turbine is used, where the maximum is over each 10 minute period. Figure 3a compares the normalized blade root maximum moments on blade 1 root for a 10 day period with that from a 100 day period during normal operation of the turbine. The blade moment normalization is done over a random 1 day extreme blade root flap moment. Thus it can be seen from Fig. 3 that the 100 day extreme flap moment is about 18% higher than the random sampled 1 day extreme moment. For computing an extrapolated flap moment magnitude, 28 random samples of extreme flap moments were considered at each mean wind speed, between 5m/s and 17m/s, since above 17m/s mean wind speed, there were limited measured samples for this short period. Each sample load was normalized with the one day extreme magnitude that was measured. Figure 3b displays the result of the load extrapolation performed using Eq. (1).

It can be seen from Fig. 3, that using this limited measured set, the 50 year extreme flap moment is predicted to be about 30% higher than the 1 day extreme and the 1 year extreme flap moment is predicted to be about 21% higher than the 1 day extreme. Based on this single case and

$$P(F_e > F) = \sum_{i=cutin}^{cutout} \left\{ \left(e^{-\pi \left(\frac{v_i - \Delta v_i / 2}{2v_{ave}} \right)^2} - e^{-\pi \left(\frac{v_i + \Delta v_i / 2}{2v_{ave}} \right)^2} \right) \left(1 - \left(e^{-e^{-(a(v_i)F^2 + b(v_i)F + c(v_i))}} \right)^{n_i} \right) \right\} \quad - (1)$$

comparing the results in Fig. 3b with that displayed

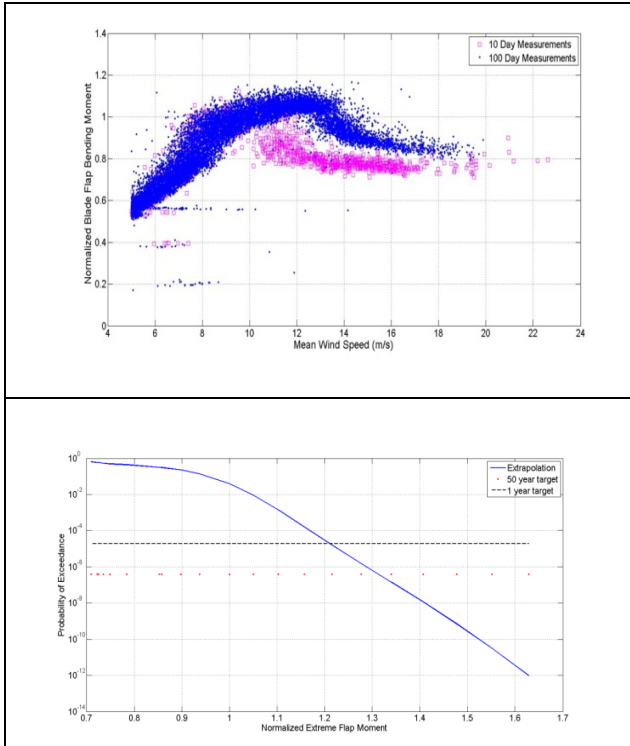


Figure 3 : a) Blade root flap moment normalized by the peak blade root flap moment obtained over a random day and b) the extrapolated extreme Flap Moment showing similar magnitudes up to the one year probability of exceedance.

in Fig. 3a, it can be seen that the extreme load extrapolation is predicting reasonable trends. However this will need to be further validated with further random samples of blade root moments. It is assumed that the measurement period of six months over which reliable operational measurements were acquired provides the load level for a general six month period even though it is only “a measurement period”.

4. Blade Root Resultant Moment

Conventional design practice is to extrapolate the blade root flap moment and obtain a contemporaneous edge moment based on a characteristic load level from simulation. The

resulting design load combination can be compared with the combination of the extrapolated edge moment with the contemporaneous flap moment. However the method of choosing the contemporaneous load value as described earlier is left to the designer and particularly for the blade root moments; this can cause a wide variation in the combined design load level. For the purpose of ultimate stress design, it is not only the combined load magnitude, but also its direction which is important as the direction of the resultant moment when perpendicular to a strain hotspot can be design driving, even if the magnitude of the moment is lower than that obtained in a different direction. Consequently it is more reasonable to use the blade sectional resultant moment as the load variable of choice and to determine its 50 year extrapolated value. The 50 year resultant moment is then assigned a direction that produces the highest strain level in the blade section. This provides a reproducible design load level without the uncertainty of selecting contemporaneous load values when only a pair of design loads is required.

Figure 4 depicts the maximum resultant blade root moment over a six month period normalized with the same one day maximum as used in Fig.3.

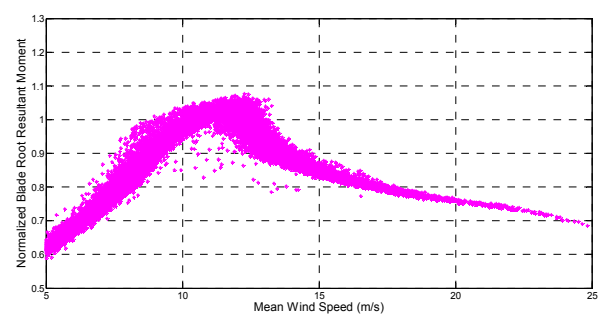


Figure 4: Extreme blade root resultant bending moment over a six month measurement period

However in contrast to Fig.3, Fig. 4 shows that the extreme resultant moment in six months is only 8% higher than the one day moment. This is interesting

since the extreme flap moment using the same normalizing method and the same 1 day load level shows an 18% increase over 100 days and therefore it implies that the coincident edge moments at the time of the largest flap moments are relatively small and therefore there is no occurrence of maximum edge and maximum flap moments together.

Figure 4 is also an ideal test for load extrapolation as it can be verified if the low levels of magnification over the one day load magnitude can be seen also upon extrapolation as in the measurement. Using Eq. (1) and 30 random extreme measurements at each mean wind speed between 5m/s and 19m/s (above which there is insufficient 10 minute samples), the extrapolated resultant moment is determined in Fig. 5. The result reveals that the extrapolated resultant moment is a bit conservative with the one year load level to be 21%

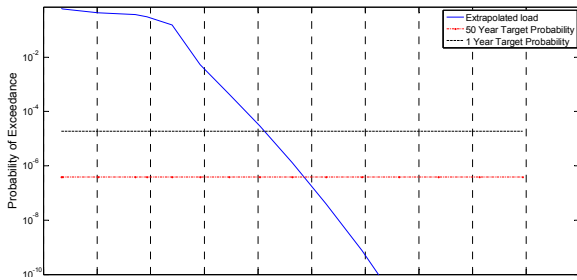


Figure 5 : Extrapolated Resultant Moment based directly using Eq. (1) with 30 samples per mean wind speed

higher than the one day level, even though measurements show less than 8% increase in 6 months. This is a common issue with load extrapolation whereby the extrapolated load level depends on the goodness of the parametric fit of the sampled data to the stochastic distribution.

5. Extrapolation Constraints.

In order to reduce the conservatism in the extrapolated load level and to ensure goodness of fit to sampled loads, Eq. (1) needs to be constrained with criteria that can provide robustness to

variations in sampled loads. Equation (1) is the theoretical asymptotic solution for Poisson processes [6,7]. However we do not have loads data that are asymptotic in the tail as it is restricted to only 30 random measurements per wind speed bin. Therefore the following additional constraints are now imposed:

- 1) In Eq. (1), to ensure the exponent is never negative and that the exceedance tail behavior asymptotically approaches its minimum of 0, the coefficients are constrained as $a, c > 0$ & $b < 0$
- 2) Further, it is possible that only a subset of the 30 data points is required to establish a robust fit. The correct sample of data points from the overall set is determined based on the condition that the derivative of the exponent is a maximum over the sampled data points as compared to any other data sample.

$$\left(\frac{d\tau}{dF}\right)_{i=1\dots m} > \left(\frac{d\tau}{dF}\right)_{i=1\dots n \neq m} \quad \forall i 1..n \quad -(2)$$

Where τ is the exponent of the quadratic exponent in Eq. (1), n is the total number of data samples used in the fitting process and m is the number of data samples that maximizes the derivative of τ with the load F .

6. Validation of the Extrapolated Load Level

The maximum blade root flap moments, edge moments and resultant moments over six months operation is considered, where each maximum is over a 10 minute period. The maxima are normalized with the same one day maximum used earlier for each of the load components. To perform load extrapolation, 30 random maxima at each mean wind speed is used for each of the load components. The load extrapolation was done by using Eq. (1) with the constraints delineated in the

last section including Eq. (2). The desired result is that the one year extrapolated load value should be within the vicinity of the load level obtained using the 6 months of measurements, but higher than the measured maximum.

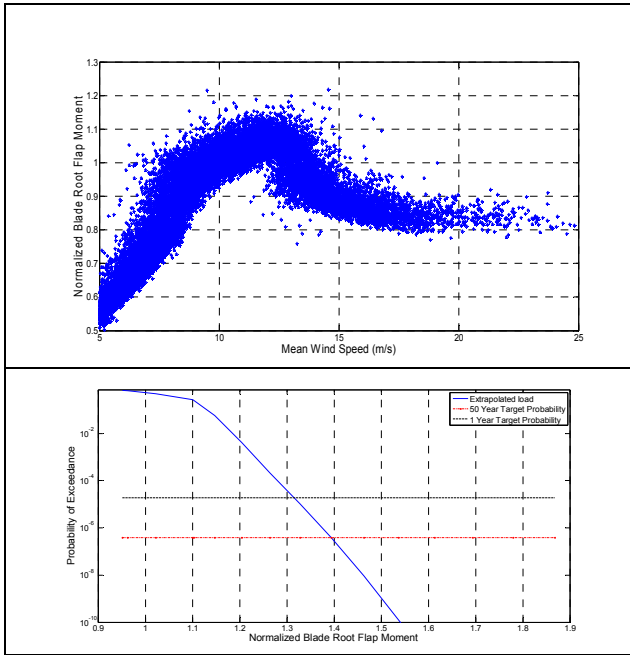


Figure 6 : a) Blade root flap moment over 6 months normalized by the peak blade root flap moment obtained over a random day and b) the extrapolated extreme Flap moment obtained using 30 maxima at each mean wind speed.

It should be emphasized that the measured 6 month extreme is “a 6 month extreme” and not “the 6 month extreme” since there can be many such six month extremes in the life of the turbine which may possess different extremes. However we assume that the six months of operation is indicative of the magnification in load level over such a period relative to a random sampled loads subset. Figure 6 provides the results for the blade root flap moment which shows that the one year extreme extrapolated blade root moment is slightly conservative, being 32% higher than the one day maximum, whereas the measured 6 month extreme was 22% higher than the one day maximum.

Figure 7 provides the same analysis for the blade root edge moment wherein again the extrapolated one year edge moment (23%) is slightly higher than the measured six month extreme (17%).

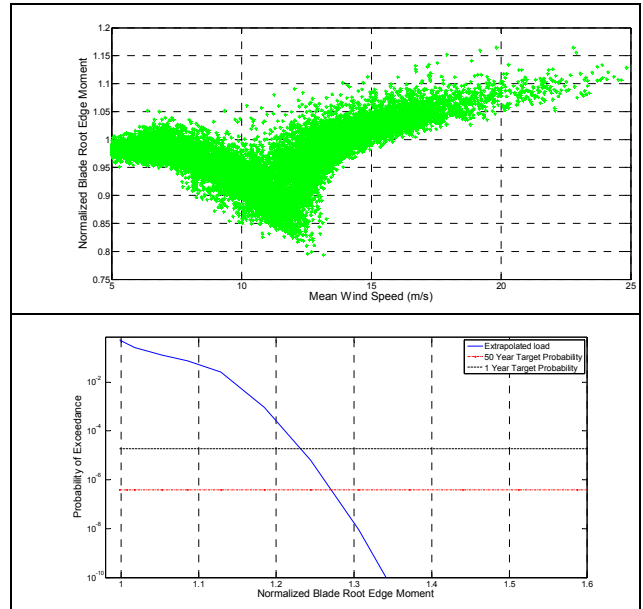


Figure 7 : a) Blade root edge moment over 6 months normalized by the peak blade root edge moment obtained over a random day and b) the extrapolated extreme edge moment obtained using 30 maxima at each mean wind speed.

Both Figs. 6 and 7 show acceptable scaling of the magnitudes with extrapolation. The approach is now repeated for the blade root resultant moment where the measurements revealed mild upscalings in the load maxima. Figure 8 depicts the result of load extrapolation for the blade root resultant moment with the constraints described in the previous section included. The extrapolated one year load is now only 7% higher than the random one day maxima, very near the measured 6 months extreme, which is 8% higher than the one day maxima.

This trend is now different than observed in Fig. 5 and is consistent with the 6 month measurement of extremes. Therefore using a constrained parametric fitting of the sampled data to the stochastic distribution, the extrapolated one year load is shown

to approach the measured maximum load trends reasonably for all combinations of the blade root moments.

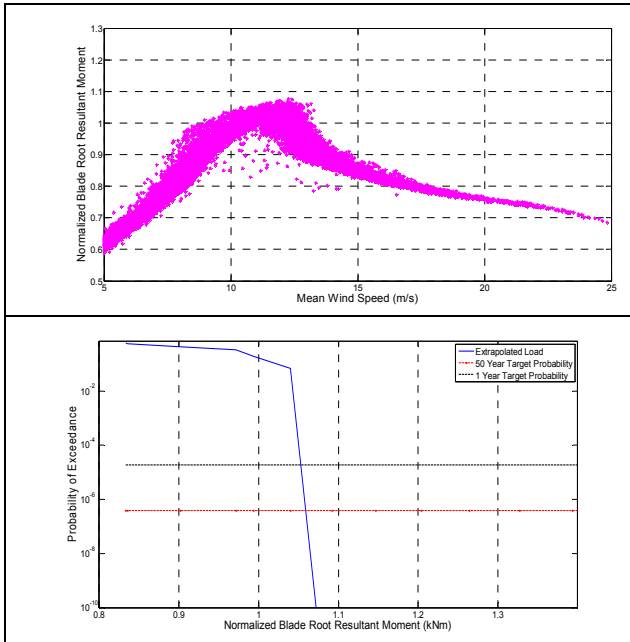


Figure 8 : a) Blade root resultant moment over 6 months normalized by the peak blade root resultant moment obtained over a random day and b) the extrapolated extreme resultant moment obtained using 30 maxima at each mean wind speed.

7. Conclusions

Measured maximum blade root moments and mean wind speed were taken under normal operating conditions from a Siemens 3.6MW offshore wind turbine. The measurements in normal operation of the turbine spanned a duration of 6 months. The normalized maximum blade root flap moment, edge moment and resultant moment were used to benchmark the corresponding extrapolated one year extreme load blade root moment. The following conclusions can be made from the investigations:

1. Based on the measurements, the blade resultant moment displayed consistent maxima that were bounded and stayed below 10% magnification when comparing 6 month extremes with a 1 day

extreme as opposed to flap and edge moments, which showed about 25% magnification.

2. If the blade design ultimate strain levels are computed based on flap and edge components of loads only, then it is robust to extrapolate the resultant moment and resultant forces on a blade section than to determine contemporaneous loads to primary extrapolated loads. The extrapolated resultant moment or force can be set in the direction that maximizes the bending strains at that section, during blade design.
3. The extrapolation method was calibrated based on selecting the data set that maximized the derivative of the exponent of the quadratic Gumbel distribution. This ensures the best fit to the sampled data set.
4. The resulting one year extrapolated load level showed acceptable and similar magnitudes as compared with the measured extreme loads over 6 months for all three blade root load components, the flap moment, edge moment and resultant moment.

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References

1. International Standard, Wind Turbines—Part 3: *Design Requirements for offshore wind turbines* IEC 61400-3 Ed. 1 2009.
2. Natarajan, A. and Verelst, D., “Outlier robustness for wind turbine extrapolated extreme loads”, *Wind Energy*, Vol. 15, No. 5, 2012, p. 679-697.

3. International Standard, Wind Turbines—Part 1: *Design Requirements*, IEC 61400–1 Ed. 3, Amendment 1, 2010
4. Koukoura, C., Natarajan, A., Kristensen, O.J., Krogh, T., “Offshore Wind Turbine Foundation Model Validation with Wind Farm Measurements and Uncertainty Quantification”, *Proceedings of the 23rd ISOPE Conference*, Anchorage, Alaska, 2013.
5. Courtney, M ; Wagner, R ; Friis P, T ; Bardon, M ; Davoust, S, Calibrating Nacelle LIDARS, *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition*, EWEA - The European Wind Energy Association, 2012
6. Natarajan A. and Holley, W.E., Statistical Extreme Load Extrapolation with Quadratic Distortions for Wind Turbines, *Journal of Solar Energy Engineering-Transactions of the ASME*, 2008, 130 (3): 031017,
7. Madsen, H.O., Krenk, S. & Lind, N.C., *Methods of Structural Reliability*, Prentice Hall, 1986